Reliability assessment of the hydraulic system of wind turbines based on load-sharing using survival signature

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Abstract

The hydraulic system is one of the most critical subsystems of wind turbines. It is used to reset the aerodynamic brakes. Because of this, the reliability of the hydraulic system is important to the functioning of the entire wind turbine. To realistically assess the reliability of the hydraulic system, we propose in this article the load-sharing based reliability model using survival signature to conduct system reliability assessment. In addition, due to the uncertainty of the failure rates, it is difficult to conduct accurate reliability analysis. The Markov-based fuzzy dynamic fault tree analysis method is developed to solve this issue for reliability modeling considering dynamic failure characteristics. Following this, we explore the reliability importance and the reliability sensitivity of redundant components. The relative importance of the components with respect to the system reliability is evaluated and ranked. Then the reliability sensitivity with respect to the distribution parameters of redundant components is studied. The results of the reliability sensitivity analysis investigate the effects of the distribution parameters on the entire system's reliability. The effectiveness and feasibility of the proposed methodology are demonstrated by the successful application on the hydraulic system of wind turbines.

Keywords: Wind turbines, Load-sharing, Reliability assessment, Survival

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Nomenclature	
$x_{i,j}$	number of jth components in subsystem i.
$c_{i,j}, s_{i,j}$	cost and space for the jth components in subsystem i.
$\tilde{\lambda}_i, \tilde{\gamma}_i$	scale and shape parameters of components taking shared loads.
λ_i, γ_i	shape and shape parameters of components taking full loads.
$\boldsymbol{N}$	set of subsystems without redundancy design.
$\boldsymbol{L}$	set of subsystems with redundancy design using load-sharing.
$\boldsymbol{M}$	set of subsystems' number of different components.

signature, Reliability sensitivity, Reliability importance

1. Introduction

With the increasing number of wind turbines installed across the world, higher standards of wind turbine reliability are now needed due to their complex structure and the high cost of maintenance and repair. The hydraulic system is one of the most critical subsystems in wind turbines (WTs). It plays a vital role in the yaw braking, pitch braking and drivetrain braking of WTs. In reality, due to the complex working environment and variable operating conditions, hydraulic systems have high failure rates [1, 2]. This is especially true in the current circumstances where tower height, rotor diameter, and overall turbine weights have almost quadrupled in size and capacity [3, 4]. It is therefore necessary to analyze and improve the reliability of the hydraulic system of the wind turbine.

In practical applications, the redundancy design is commonly used to improve the reliability of complicated systems with high failure rates. Components in the redundancy system can share the workload. For example, two components share the total load if both components function well, or one component will take the total load if the other one fails. However, the redundancy system is treated as a parallel system in much research [5]. Liu et al. [6] presented a novel reliability model of the load-sharing system that can solve the effects of the arriving loads and the components' failures on the degradation of the survival components assuming that components degrade continuously. Ling et al. [7] developed an equal load-sharing model for the series system using autopsy data and studied the effects of active redundancy on system reliability. However, the components are of the same type, and the number of redundant components is limited to one. Zhao et al. [8] explored a reliability analysis of load-sharing system considering the component degradation under the assumption that all components in the system are of the same type and suffer the equal workload.

The concept of reliability importance was firstly introduced by Birnbaum in 1960s [9]. Reliability importance plays an important role in practical applications, and is studied by many researchers. Kuo and Zhu [10] developed importance measures from individual components to groups of components and extended importance measures for s-independent components. Zhong and Li [11] studied component importance and sensitivity analysis in deterministic structures and non-deterministic structures. Baraldi et al. [12] explored the effects of epistemic uncertainties on the component ranking using Birnbaum Importance Measure and Possibility Theory. Kamalja and Amrutkar [13] developed a simplified and efficient formula for the assessment of reliability importance measures of the weighted-consecutive-system. Zhu et al. [14] studied the Joint Reliability Importance analysis of Markov-dependent components. Borgonovo et al. [15] proposed an important measure methodology based on the mean time to failure (MTTF), which shows intuitive probabilistic and geometric interpretations. Geng Feng et al. [16] introduced a simulation method based on survival signature to analyze the imprecise system reliability and implement the relative importance index of each component. Eryilmaz et al. [17] developed the marginal and joint reliability importance for the coherent system. Huang et al. [18] applied reliability importance analysis on the phased mission system (PMS) and explored the effects of each component in each phase on the reliability. However, the above research did not explore the effects of probabilistic characteristics of components on reliability importance analysis and reliability sensitivity analysis of the system.

Component failure rates are dynamic and fuzzy, and a failure in one component can affect other components. These characteristics of the hydraulic system make it difficult to use the traditional reliability method to analyze system reliability. Markov-based dynamic fault tree analysis (DFTA) not only has the function of the conventional fault tree analysis (FTA) method but also can model and evaluate the reliability of the problem with dynamic failure characteristics. Zhu et al. [19] transferred the dynamic fault tree (DFT) model to the Markov model and proposed the quantitative reliability characterization based on the Markov model with the DFT. Amari et al. [20] developed a novel method for solving the DFT model, which can improve the calculation speed and accuracy. Li et al. [21] introduced a fuzzy Markov model to capture the dynamic behavior of systems and evaluate the reliability of the computer numerical control (CNC) using this method. A fuzzy continuous-time Markov model with finite discrete states was also proposed to assess the fuzzy state probability of multi-state elements at any time instant [22, 23]. Wang et al. [24] explored a novel conception of incomplete common cause failure that can do the quantitative analysis of a system.

As can be seen from the above literature, redundant components are treated as a parallel system, which may reduce the system reliability value and lead to excessive reliability estimations and high costs of the system. We therefore propose the load-sharing using survival signature to deal with this issue. Due to the uncertainties of failure rates, fuzzy dynamic fault tree (FDFT) is used to study the effects of uncertainties of failure rates on the system reliability. Following this, we conduct reliability importance analysis and reliability sensitivity analysis of the hydraulic system of the wind turbine. The rest of this paper is organized as follows. Section 2 briefly introduces the structure and working mechanism of the hydraulic system of the wind turbine. Section 3 proposes the load-sharing formulation using survival signature. In addition, survival signature, reliability sensitivity, and fuzzy dynamic fault tree are also presented in this section. Section 4 gives the reliability-redundancy allocation model and obtains the optimal solution using the genetic algorithm. Following this, Section 5 shows the DFT based reliability model and load-sharing based reliability model using survival signature. Section 6 presents the results and offers discussion of them. Section 7 summarises some conclusions of this article.

2. Hydraulics system of wind turbines

The WT hydraulic system is used to reset the aerodynamic brakes of the wind turbine. It provides the power for the brake system, and mainly completes the start and stop tasks of the wind turbine. It consists of two pressure-holding circuits: one is supplied to the yaw brake system through the accumulator, and the other is supplied to the brake system of the high-speed shaft through the accumulator. The function of these two circuits is to keep the pressure of the hydraulic system constant. To make the hydraulic system compact and easy to be installed, repaired and overhauled, two circuits are integrated into the same hydraulic station in the wind turbine. Fig. 1 is a schematic diagram of the WT hydraulic system. It is composed of a tank (1), a pump (2), three overflow valves (3,11,13,15), a one-way valve (4,5), a filter (6), a shut-off valve (7), a cylinder of the yaw brake (8), four two-way two-position solenoid directional control valves (9,10,14,16), the pressure sensor (12), the cylinder of the high-speed shaft brake (17), a accumulator (18), a pressure relay (19), a air-filter (20), a liquid-level meter (21), and a thermometer (22).

The accumulator (18) and the pressure sensor (12) are two critical auxiliary components in hydraulic systems. Since the system pressure often leaks, the accumulator is used to hold pressure. When the pressure of the accumulator (18) is lower than that of the pressure sensor (12), the hydraulic pump starts to supply pressure to the system; when the value of the pressure sensor (12) reaches the set value, the hydraulic pump stops working to keep the pressure of the accumulator (18) at the set value. The accumulator and pressure sensors therefore play an essential role in the hydraulic system.

According to the control strategy of the wind turbine, the WT needs to be braked in the yaw circuit when it faces the wind. When the wind direction changes, it still needs to provide the braking force by the hydraulic system, which can prevent WT vibration and ensure the accuracy of the yaw. When the cable twists for a certain number of turns, the nacelle needs to rotate in the reverse direction to keep the cable safety, then the yaw brake is released completely. Therefore, the hydraulic system needs to provide three kinds of pressure states for the yaw brake [25]. The overflow valve (3) is used to set the system pressure, and the overflow valve (11) is used to set the pressure when facing the wind. When the WT is facing the wind, the solenoid directional control valve (9 and 10) lose electricity, and the yaw brake (8) works at setting pressure; when the main control system sends out the yaw instruction, unit (9) loses electricity and unit (10) gains electricity. At this time, brake (8) begins to function.

The braking circuit of the high-speed shaft begins to function when the WT needs to be repaired or meets the extreme weather, which can ensure that the WT drivetrain is at rest. When the WT is forced to stop for the safety, the reversing valve (14) gains electricity, and unit (16) loses electricity; then it begins to be braked; the WT starts up when unit (16) gains electricity.

3. Methodology

3.1. Load-sharing

In reality, the quantification of the system's reliability of redundant components is determined based on the assumption that when one redundant component fails, the reliability of surviving components does not change during the mission. However, according to the failure mechanism of the redundancy systems, once the redundant components fail, the surviving components will take the full load, their failure rates will increase, and their reliability will decrease. Therefore, this assumption is not feasible and effective in practical situations. For this reason, it is essential to take load-sharing into consideration in the reliability analysis.

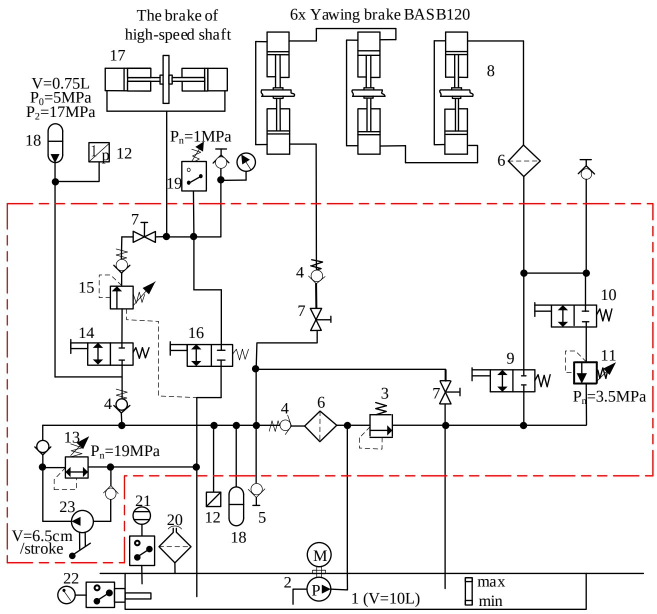

Figure 1: Schematic of hydraulic system of the wind turbine

Let us consider a two-component redundancy system in which the mechanical components follow the two-parameter Weibull distribution and the electronic components follow the exponential distribution. There are three system success function modes for a system of two load-sharing redundant components: both components function, component A fails while component B functions, and component A functions while component B fails. The state transition diagram of a two-component redundancy system is depicted in Fig. 2. Fig. 2 shows the failure mechanism of the two-component redundancy system. In the state one, two components functions and share the full load L_1. Component 1 and component 2 take the load k_1L_1 and k_2L_1, respectively. One component will fail at state two where the surviving component will suffer the full load L_1. The entire system will fail when two components go bad at state three. Hence, there are three situations of system success function where at least one component functions during the mission. More detailed information can be found in references by Liu [26] and Mattas [27].

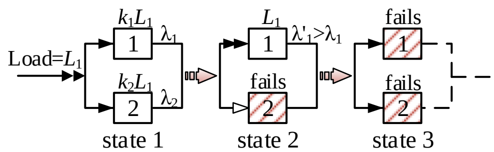

Figure 2: Load-sharing with two redundant components ($k_1 + k_2 = 1$)

The system's reliability function at time t can be quantified by

$$
\begin{aligned}
P(T_s > t) = & R_1^r(t) \cdot R_2^r(t) + \int_0^t R_2^r(t_1) \cdot R_2(t|t_1) \cdot f_1^r(t_1) dt_1 \\
& + \int_0^t R_1^r(t_2) \cdot R_1(t|t_2) \cdot f_2^r(t_2) dt_2
\end{aligned} \tag{1}
$$

where $R_i(t) = 1 - F_i(t)$ is the reliability function of component i at time t being $i = 1, 2$, $F_i(t)$ is the lifetime distribution function of component i at time t, $F_i(t) = 1 - e^{-(\lambda t)^\gamma}$; $R_i^r(t)$ is the reliability function of component i taking the reduced load at time t; $R_i(t|u) = P(T > t|T > u)$ means the reliability of component i taking the full load switched from the reduced load at time u; $f_i^r(t)$ represents the probability density function of component i taking the reduced load at time t.

Calculating each term of equation (1), we can obtain the formula of the system's reliability for a mission of duration t. Therefore, the equation (1) can be rewritten as follows

$$
\begin{aligned}
R_{sys}(t) = & e^{-(\lambda_1 \cdot t)^{\gamma_1}} \cdot e^{-(\lambda_2 \cdot t)^{\gamma_2}} + \int_0^t \gamma_1 \lambda_1^{\gamma_1} t_1^{\gamma_1 - 1} \\
& \cdot e^{-\left((\lambda_1 t_1)^{\gamma_1} + \left[\lambda'_2 \left(t - t_1 + \frac{1}{\lambda'_2} e^{(\lambda_2 t_1)^{\gamma_2/\gamma'_2}} \right) \right]^{\gamma'_2} \right)} dt_1 + \int_0^t \gamma_2 \lambda_2^{\gamma_2} \\
& \cdot t_2^{\gamma_2 - 1} \cdot e^{-\left((\lambda_2 t_2)^{\gamma_2} + \left[\lambda'_1 \left(t - t_2 + \frac{1}{\lambda'_1} e^{(\lambda_1 t_2)^{\gamma_1/\gamma'_1}} \right) \right]^{\gamma'_1} \right)} dt_2
\end{aligned} \tag{2}
$$

In addition, if the lifetime distribution of components follows the exponential distribution, the formula of the system's reliability for a mission at time t is derived as follows

$$
\begin{aligned}
R_{sys}(t) = & e^{-\lambda_1 t} \cdot e^{-\lambda_2 t} + \int_0^t \lambda_1 \cdot e^{-\lambda_1 t_1} \cdot e^{-\lambda_2 t_1} \cdot e^{-\lambda_2^{'}(t-t_1)} dt_1 \\
& + \int_0^t \lambda_2 \cdot e^{-\lambda_2 t_2} \cdot e^{-\lambda_1 t_2} \cdot e^{-\lambda_1^{'}(t-t_2)} dt_2
\end{aligned}
\tag{3}
$$

where λ_i is the rate parameter of component i being $i = 1, 2$, $\lambda_i^{'}$ means the rate parameter of the surviving component i while the other component fails, t_i represents the time when the component i fails.

3.2. Survival signature

The system signature can only be used for systems with a single type of component [28]. In reality, most systems tend to be more and more complicated and have components of multiple types. In addition, the system signature is closely related to the structure of the system for the system reliability analysis. To overcome this drawback of the system signature, Coolen and Coolen-Maturi [29] firstly proposed the "survival signature" to explore the system reliability with multiple types of components.

Consider a coherent system that consists of m components of $K \geq 2$ types, with m_k components of type $k \in \{1, 2, \cdots, K\}$ and $\sum_{k=1}^{K} m_k = m$. Let $\Phi(l)$ ($l = 1, 2, \cdots, m$) denote the probability that the system functions. If we assume that there are exactly l components functioning, then the remaining $m-l$ components do not function. Two assumptions are made in this study: (i) The failure times of components of the same type are exchangeable (iid); (ii) The failure times of components of different types are independent. To group components of the same types, the state vector $\underline{x} = (\underline{x}^1, \underline{x}^2, \cdots, \underline{x}^K) \in \{0, 1\}^m$ with the sub-vector $\underline{x}^k = (x_1^k, x_2^k, \cdots, x_{m_k}^k)$ is introduced to represent the states of components of the type k ($\sum_{i=1}^{m_k} x_i^k = l^k$). The structure function is defined in equation (4). The system's survival function is represented by $\Phi(l_1, l_2, \cdots, l_K)$ that means the probability that the system functions in the condition that exactly l_k of type k

components function, for $l_k = 0, 1, \cdots, m_k$.

$$\phi(\underline{x}) = \begin{cases} 0, & \text{system does not function,} \\ 1, & \text{system functions.} \end{cases} \tag{4}$$

There are $\binom{m_k}{l_k}$ state vectors $\underline{x}^k$ with exactly l_k of its m_k components $x_i^k = 1$. The set of the state vectors for components of type k is denoted by S_l^k. Let $S_{l_1,\cdots,l_K}$ represents the set of all state vectors for the system. All state vectors $\underline{x}^k \in S_l^k$ are equally likely to occur because the failure times of m_k components of type k are interchangeable. Therefore, $\Phi(l_1, l_2, \cdots, l_K)$ can be obtained by

$$\Phi(l_1, l_2, \cdots, l_K) = \left(\prod_{k=1}^{K} \binom{m_k}{l_k}^{-1} \right) \times \sum_{S_{l_1,\cdots,l_K}} \phi(\underline{x}) \tag{5}$$

Let $C_t^k \in \{0, 1, \cdots, m_k\}$ denote the number of type k component in the system that function at time $t > 0$. Using the failure times of components of different types and the reliability function $R_k(t) = 1 - F_k(t)$, the entire system's reliability can be expressed as

$$\begin{aligned} R_{sys}(t) = \sum_{l_1=0}^{m_1} \cdots \sum_{l_K=0}^{m_K} \Bigg[& \Phi(l_1, l_2, \cdots, l_K) \\ & \cdot \prod_{k=1}^{K} \left(\binom{m_k}{l_k} [R_k(t)]^{l_k} \, [1 - R_k(t)]^{m_k - l_k} \right) \Bigg] \end{aligned} \tag{6}$$

3.3. Reliability importance and reliability sensitivity

Reliability importance is very different from reliability allocation. The invariant optimal allocation is an allocation related only to the relative ordering rather than the magnitude of the component reliabilities [30]. Reliability importance and reliability sensitivity of a component actually measure the importance level and effects of the role of the component to the entire system. In reality, reliability importance and reliability sensitivity are quite useful to the designers, which can help optimize the allocation of the reliability of different components, allocate resources for inspection activities, and develop optimal maintenance policies.

The reliability importance of the type i component can be derived from equation (6)

$$\frac{\partial R_s(t)}{\partial R_i(t)} = \sum_{l_1=0}^{m_1} \cdots \sum_{l_K=0}^{m_K} \left[\frac{l_i - m_i R_i(t)}{R_i(t)[1 - R_i(t)]} \Phi_s(l_1, l_2, \cdots, l_K) \right.$$
$$\left. \cdot \prod_{k=1}^{K} \left(\binom{m_k}{l_k} [R_k(t)]^{l_k} [1 - R_k(t)]^{m_k - l_k} \right) \right] \tag{7}$$

In engineering practice, systems often have more than one type of components that play different roles during a mission. Moreover, the reliability importance and reliability sensitivity with respect to distribution parameters of components are quite different. For example, in a wind turbine, bearings and gears are consistently allocated higher reliability than that of other components due to their special positions and important functions. To keep the balance between reliability and the cost of the entire system, the designers have to explore the reliability importance and reliability sensitivity of each component and assembly. Assuming that no components are of the same type, the reliability importance and reliability sensitivity of the system with respect to distribution parameters of each component can be obtained from equation (7) and (8).

The reliability sensitivity of the system with respect to distribution parameters of type i component is

$$\frac{\partial R_s(t)}{\partial p_i^{(l)}} = \frac{\partial R_s(t)}{\partial R_i(t)} \frac{\partial R_i(t)}{\partial p_i^{(l)}} \tag{8}$$

The structural importance can measure the importance of the components' position. In this paper, we develop the reliability sensitivity considering the structure importance of type i component using survival signature.

$$\frac{\partial R_s(t)}{\partial p_i^{(l)}} = \sum_{\underline{x}^k} \left[R(1_i, \underline{x}^k) - R(0_i, \underline{x}^k) \right] \frac{\partial R_i(t)}{\partial p_i^{(l)}} \tag{9}$$

where $i = 1, 2, \cdots, m_K$,

$$I_i^B = \sum_{\underline{x}^k} \left[R_s(1_i, \underline{x}^k) - R_s(0_i, \underline{x}^k) \right] \tag{10}$$

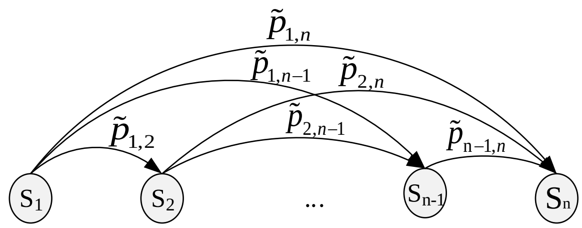

Figure 3: Fuzzy state transition diagram of the system

is the structure function of component i. $R_s(1_i, \underline{x}^k)$ and $R_s(0_i, \underline{x}^k)$ represent the reliability of the system at state vector $\underline{x}^k$ given the component i functions and fails.

3.4. Fuzzy dynamic fault tree

The static fault tree considers neither the uncertainty of failure rates nor the degradation of the equipment. The fuzzy dynamic fault tree (FDFT) has significant advantages over the static fault tree. The FDFT combines the Markov chain and the fuzzy theory to model and assess the reliability of complex systems with dynamic failure characteristics and fuzzy failure rates [31].

Assuming that the system has n states $(S_1, S_2, \cdots, S_n)$ before failure and S_i is the state space of the Markov process $\{S(t), t \geq 0\}$, the Markov model is established to transform n states. Fig. 3 shows the fuzzy state transition diagram of the non-repairable system. Fuzzy failure probabilities are used to represent the state transition rate due to the difficulty of estimating accurate values. The matrix of fuzzy state transition rate is shown in equation (11).

$$\tilde{S} = (\tilde{P}_{i,j}) = \begin{array}{c} \text{state} \\ 1 \\ 2 \\ \vdots \\ n \end{array} \begin{array}{c} \begin{array}{cccc} 1 & 2 & \cdots & n \end{array} \\ \begin{bmatrix} \tilde{p}_{1,1} & \tilde{p}_{1,2} & \cdots & \tilde{p}_{1,n} \\ \tilde{p}_{2,1} & \tilde{p}_{2,2} & \cdots & \tilde{p}_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{p}_{n,1} & \tilde{p}_{n,2} & \cdots & \tilde{p}_{n,n} \end{bmatrix} \end{array} \tag{11}$$

The fuzzy transition rates are brought into the Markov model to obtain the differential equation corresponding to the specific state [32]. Therefore, the differential equations with the fuzzy transition rate take the form of

$$\begin{cases} \frac{\mathrm{d}\tilde{f}_1(t)}{\mathrm{d}t} = -\tilde{f}_1(t)\sum_{j=2}^{n}\tilde{p}_{i,j} \\ \frac{\mathrm{d}\tilde{f}_i(t)}{\mathrm{d}t} = \sum_{j=i}^{i-1}\tilde{f}_j(t)\tilde{p}_{j,i} - \sum_{j=i+1}^{n}\tilde{f}_i(t)\tilde{p}_{i,j} \\ \frac{\mathrm{d}\tilde{f}_n(t)}{\mathrm{d}t} = \sum_{j=1}^{n-1}\tilde{f}_j(t)\tilde{p}_{j,n}, 1 < i < n, t \geq 0 \end{cases} \tag{12}$$

To simplify equations for the calculation, the differential equations (12) are transformed using the Laplace transform with the help of the initial conditions: $\tilde{p}_1(0) = 1$, $\tilde{p}_i(0) = 0$ $(i \neq 1)$. Then the corresponding linear equations are obtained as follows

$$\begin{cases} s\tilde{f}_1(s) = -\tilde{f}_1(s)\sum_{i=2}^{n}\tilde{p}_{1,i} + 1 \\ s\tilde{f}_i(s) = \sum_{j=1}^{i-1}\tilde{f}_i(s)\tilde{p}_{j,i} - \sum_{j=i+1}^{n}\tilde{f}_i(s)\tilde{p}_{i,j} \\ s\tilde{f}_n(s) = \sum_{j=1}^{n-1}\tilde{p}_{j,n}\tilde{f}_i(s), 1 < i < n \end{cases} \tag{13}$$

The function $\tilde{f}_i(s)$ can be obtained by solving the linear equations (13) using the inverse Laplace transform. Then according to the extension principle, the lower bounds and upper bounds of $\tilde{f}_i(t)$ are calculated.

4. Reliability-redundancy allocation of hydraulic system

Redundancy design is most effective when applied at the weakest component in the hierarchical system. In reality, we often treat the redundant components as parallel systems, which may lead to lower system reliability than normal. Due to this reason, some components and assemblies are too high, however, the reliability of some critical components and assemblies are not high enough. A system with high reliability will in most cases lead to the high cost of the system. Therefore, not only manufacturers but also operators want to develop a better strategy of reliability-redundancy allocation than before, which can help significantly reduce the cost of the entire system. To balance the system reliability and the system cost, we introduce the load-sharing under the survival signature to reliability-redundancy allocation problem of the hydraulic system of WTs.

The proposed model for load-sharing based reliability-redundancy allocation of the hydraulic system is given as follows:

$$Maximize \quad R(t;\boldsymbol{x}) = \prod_{i\in N} R_i^{sp}(t) \cdot \prod_{j\in L} R_j^{ls}(t) \tag{14}$$

Subject to:

$$g_1(\boldsymbol{x},\boldsymbol{n}) = \sum_{i=1}^{\boldsymbol{N}} \sum_{j=1}^{\boldsymbol{M}} x_{ij} \cdot s_{ij} \leq \boldsymbol{S} \tag{15}$$

$$g_2(\boldsymbol{x},\boldsymbol{n}) = \sum_{i=1}^{\boldsymbol{N}} \sum_{j=1}^{\boldsymbol{M}} x_{ij} \cdot c_{ij} \leq \boldsymbol{C} \tag{16}$$

$$\begin{aligned} R_j^{ls}(t) = & e^{-(\lambda_j^1 \cdot t)^{\gamma_j^1}} \cdot e^{-(\lambda_j^2 \cdot t)^{\gamma_j^2}} + \int_0^t \gamma_j^1 (\lambda_j^1)^{\gamma_j^1} {t_1}^{(\gamma_j^1-1)} \\ & e^{-\left((\lambda_j^1 t_1)^{\gamma_j^1} + \left[\tilde{\lambda}_j^2 \left(t - t_1 + \frac{1}{\tilde{\lambda}_j^2} e^{(\lambda_j^2 t_1)^{\gamma_j^2/\tilde{\lambda}_j^2}}\right)\right]^{\tilde{\gamma}_j^2}\right)} dt_1 + \int_0^t \gamma_j^2 (\lambda_j^2)^{\gamma_j^2} \\ & \cdot {t_2}^{(\gamma_j^2-1)} e^{-\left((\lambda_j^2 t_2)^{\gamma_j^2} + \left[\tilde{\lambda}_j^1 \left(t - t_2 + \frac{1}{\tilde{\lambda}_j^1} e^{(\lambda_j^1 t_2)^{\gamma_j^1/\tilde{\gamma}_j^1}}\right)\right]^{\tilde{\gamma}_j^1}\right)} dt_2 \end{aligned} \tag{17}$$

$$1 \leq \sum_{i=1}^{N} x_{ij} \leq n_{max,j}, x_{ij} \in \{1, 2, \cdots, n_{max,i}\}$$

where $R_i^{sp}(t)$ represents the reliability of series-parallel subsystems at time t, $R_i^{ls}(t)$ means reliability of load-sharing subsystems at time t; $\boldsymbol{S}$ and $\boldsymbol{C}$ are system level constraint limits for space and cost, set of s_i and c_i, respectively.

The objective function (14) maximizes the system reliability in which the load-sharing of redundant components is considered. Components' space and cost are constraints. The costs of components in this paper are relative values. The three critical components with high failure rates are the hydraulic pump, the one-way valve, and the overflow valve. These are treated as the optimization variables represented by n_1, n_2 and n_3, respectively. Using the optimization model with equations (14)-(17), we perform some runs at different time t using the genetic algorithm. The optimal solution is obtained as $[2, 2, 2]$ with the highest reliability (0.8940) and the acceptable cost (38), which means that the hydraulic pump, the one-way valve, and the overflow valve need to be allocated a redundant component to keep them functioning reliably and safely. In addition, the designers should pay more attention to these critical components of the hydraulic system of wind turbines.

5. Reliability models of hydraulics system

5.1. DFT based reliability model

The dynamic gates are used to establish the DFT model shown in Fig.4, which considers the working principle, failure modes and failure mechanism of the WT hydraulic system. The event of the insufficiency of pressure in the circuit is taken as the top event in the following analysis. Some units are not considered due to their low failure rates.

The basic events of the fault tree are introduced as follows: E_1: the braking failure of the high-speed shaft; E_2: the circuit failure of the yaw brake; E_3: the main path failure; E_{31}: the circuit failure; E_{32}: the supply failure; X_2: the pump failure: X_3: the main overflow valve failure; X_4: the one-way valve failure; X_5: the overflow valve 5 failure; X_6: the filter failure; X_7: the shut-off valve 7 failure; X_8: the cylinder failure of the yaw brake; X_9, X_{10}, X_{14}, X_{16}: the failure of two-way two-position solenoid directional control valve; X_{11}: the overflow valve 11 failure; X_{17}: the cylinder failure of the high-speed shaft brake; X_{18}: the power accumulator failure; X_{19}: the pressure relay failure.

The DFT model can be transformed to a fuzzy Markov model using the fuzzy failure rates of the basic events. The state transition diagram of the circuit is shown in Fig. 5. In Fig. 5, S_1 means the state where the whole system works well; S_2 is the state where the oil supply fails due to the pump failure; S_3 represents the oil supply failure caused by the failure of pressure relay; S_4 represents the oil supply failure caused by the failure of the power accumulator; S_5 represents the failure of the entire system.

Table 1: Parameters of components in hydraulics system (Components' MTBFs from CSIC (Chongqing) Haizhuang Windpower Equipment Co., Ltd)

Events	Name	Distribution	MTBF($\times 10^5$h)	γ	$\lambda(\times 10^{-6})$
X_2	Hydraulic pump	Weibull	4.1298	2	2.1459
X_3	Main overflow valve	Exponential	1.7544	-	5.7000
X_4	One-way valve	Exponential	3.2120	-	3.1133
X_5	One-way valve	Exponential	549.45	-	0.0182
X_6	Filter	Exponential	14.6007	-	0.6849
X_7	Shut-off valve	Exponential	43.8020	-	0.2283
X_8	Hydraulic cylinder of yaw braking	Weibull	86.7303	2	0.10218
X_9	Two-way two-position solenoid directional control valve	Exponential	1.7520	-	5.7078
X_{10}	Two-way two-position solenoid directional control valve	Exponential	1.7520	-	5.7078
X_{11}	Yaw overflow valve	Exponential	1.7544	-	5.7000
X_{14}	Two-way two-position solenoid directional control valve	Exponential	1.7520	-	5.7077
X_{15}	Overflow valve	Exponential	1.7544	-	5.7000
X_{16}	Two-way two-position solenoid directional control valve	Exponential	1.7520	-	5.7077
X_{17}	Braking hydraulic cylinder of high-speed shaft	Weibull	5.7817	2	1.5328
X_{18}	Power accumulator	Weibull	8.6723	2	1.0219
X_{19}	Pressure relay	Exponential	200.00	-	0.0500

The corresponding state transition rate matrix $\tilde{p}$ is:

$$\tilde{p} = \begin{bmatrix} -\sum_{i=2}^{11}\tilde{p}_i - \sum_{j=14}^{19}\tilde{p}_j & \tilde{p}_2 & \tilde{p}_{19} & \tilde{p}_{18} & \sum_{i=3}^{11}\tilde{p}_i + \sum_{j=14}^{17}\tilde{p}_j \\ 0 & -\tilde{p}_{18} - \tilde{p}_{19} & \tilde{p}_{19} & 0 & \tilde{p}_{18} \\ 0 & 0 & -\tilde{p}_{18} & 0 & \tilde{p}_{18} \\ 0 & 0 & 0 & -\tilde{p}_2 - \tilde{p}_{19} & \tilde{p}_2 + \tilde{p}_{19} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{18}$$

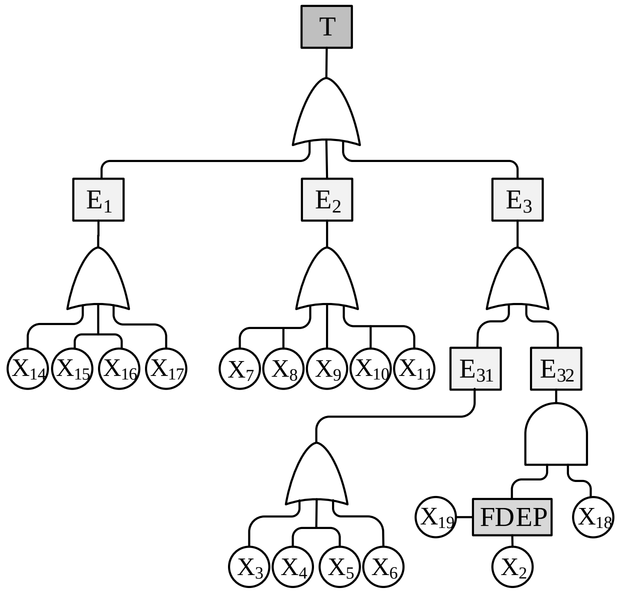

Figure 4: Dynamic fault tree of the hydraulic system

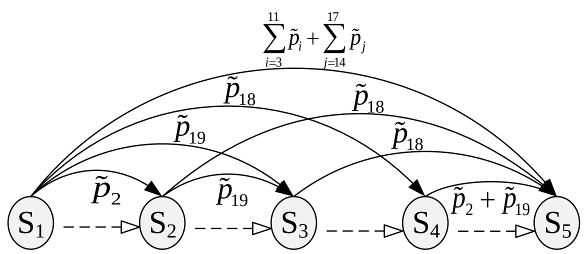

Figure 5: State transition diagram of the circuit of the hydraulic system

With the initial conditions $\tilde{f}_1(0) = 1$, $\tilde{f}_i(0) = 0$ $(i \neq 0)$, using equations (12), (13) and the inverse Laplace-Stieltjes transform, the fuzzy probabilities of each state can be computed. The fuzzy failure probability function of state 5 is derived as follows

$$\begin{aligned}
\tilde{f}_5(t) =& 1 - \frac{(\tilde{p}_2 + \tilde{p}_{19}) \cdot e^{-\tilde{p}_{18} \cdot t}}{\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{17} \tilde{p}_j + \tilde{p}_{19}} - \frac{\tilde{p}_{18} \cdot e^{-(\tilde{p}_2 + \tilde{p}_{19}) \cdot t}}{\sum_{i=3}^{11} \tilde{p}_i + \sum_{j=14}^{18} \tilde{p}_j} \\
& - \frac{\sum_{i=3}^{11} \tilde{p}_i + \sum_{j=14}^{17} \tilde{p}_j}{\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j} \cdot e^{-(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j) \cdot t} \\
& + \frac{\tilde{p}_2 \cdot \tilde{p}_{18} \cdot e^{-(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j) \cdot t}}{(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j)(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{17} \tilde{p}_j)} \\
& + \frac{\tilde{p}_{18} \cdot \tilde{p}_{19} \cdot e^{-(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j) \cdot t}}{(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j)(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j - \tilde{p}_{18})} \\
& - \frac{\tilde{p}_2 \cdot \tilde{p}_{18} \cdot \tilde{p}_{19} \cdot e^{-(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j) \cdot t}}{(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j)(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j - \tilde{p}_{18})} \\
& \cdot \frac{1}{\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{17} \tilde{p}_j} \\
& + \frac{(\tilde{p}_2 + \tilde{p}_{19}) \cdot \tilde{p}_{18} \cdot e^{-(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j) \cdot t}}{(\sum_{i=2}^{11} \tilde{p}_i + \sum_{j=14}^{19} \tilde{p}_j)(\sum_{i=3}^{11} \tilde{p}_i + \sum_{j=14}^{18} \tilde{p}_j)}
\end{aligned} \tag{19}$$

5.2. Load-sharing based reliability model using survival signature

Due to the booming development of wind power in past decades, many manufacturers of wind turbines did not pay much attention to building a mechanism for the collection of maintenance record. The only data that can be provided is the MTBF, which can not be used directly. Therefore, we need to transform MTBF into the parameters of Weibull distribution and Exponential distribution. A Weibull distribution $w(\lambda, \gamma)$ has two parameters: scale parameter λ and shape parameter γ. The *pdf* of the Weibull distribution is

$$f(t) = \lambda\gamma(\lambda t)^{\gamma-1} \cdot e^{-(\lambda t)^{\gamma}}, \quad t > 0 \tag{20}$$

The rth moment $E(T^r)$ of the distribution is[33]:

$$E(T^r) = \frac{\Gamma(1 + \frac{r}{\gamma})}{\lambda^r} \tag{21}$$

where $E(T^r) = MTBF$,

$$\Gamma(k) = \int_0^{\infty} u^{k-1} e^{-u} du \tag{22}$$

is the gamma function, $k = 1 + \frac{r}{\gamma} > 0$.

For a load-sharing system with n_t components, the failure rate of ith component of the load-sharing system at time t can be computed by

$$\lambda_i(t) = \frac{\lambda_s}{n_t} + \lambda_i \tag{23}$$

where n_t is the number of functioning components in load-sharing at time t, λ_s is the total failure rate related to the load that can be shared, λ_i is the further failure rate applying to component i.

For a lifetime distribution function that follows an Exponential distribution with parameter λ, that is, $R(t) = 1 - F(t) = 1 - e^{-\lambda t}$, the MTBF is defined as the expected value of the lifetime before a failure occurs. The MTBF can be obtained as follows

$$MTBF = \int_0^\infty R(t)dt = \int_0^\infty e^{-\lambda \cdot t}dt = \frac{1}{\lambda} \tag{24}$$

According to equation (21)-(24), the parameters of Weibull distribution and Exponential distribution can be computed. All related parameters of the distribution function of the hydraulic system are shown in Table 1. The data of MTBF in this table is real maintenance records provided by CSIC (Chongqing) Haizhuang Windpower Equipment Co., Ltd.

From section 4, the best redundancy allocation is obtained using reliability-redundancy allocation. The optimization results show that the hydraulic pump, one-way valve, and overflow valve need redundancy design that adds one more component to the corresponding components. In terms of the redundancy design of the hydraulic system, the minimal cut set of the new structure is given below:

T : $\{\mathrm{E}_1,\mathrm{E}_2,\mathrm{E}_3\}$

E_1: $\{X_{14}, X_{15}, X_{16}, X_{17}\}, \{X_{14}, X_{15}^r, X_{16}, X_{17}\}$

E_2: $\{X_7, X_8, X_9, X_{10}, X_{11}\}$

E_3: $\{X_2, X_3, X_4, X_5, X_6, X_{18}, X_{19}\}, \{X_2^r, X_3, X_4, X_5, X_6, X_{18}, X_{19}\}$,
$\{X_2, X_3, X_4^r, X_5, X_6, X_{18}, X_{19}\}, \{X_2^r, X_3, X_4^r, X_5, X_6, X_{18}, X_{19}\}$

Table 2: Survival signature of the hydraulic system

l_1	l_2	l_3	$\Phi(l_1, l_2, l_3)$
0	[0,1,2]	[0,1,2]	0
[1,2]	0	[0,1,2]	0
[1,2]	[1,2]	0	0
1	1	1	1
1	1	2	1
1	2	1	1
1	2	2	1
2	1	1	1
2	1	2	1
2	2	1	1
2	2	2	1

where $X_i^r (i = 2, 4, 15)$ means the redundant component for corresponding subsystems.

According to the minimal cut set of the new structure, the system's reliability is obtained as follows

$$R_{sys}(t) = R_{E_1}(t) \cdot R_{E_2}(t) \cdot R_{E_3}(t) \tag{25}$$

As can be seen from the redundancy allocation of the hydraulic system, the new structure involves six components of three types, $m_1 = m_2 = m_3 = 2$. We explored the system reliability in the case that if one component fails but the other one still functions, the survival component will take the full load or if both components are good, they will share the full load. Of course, the load-sharing can reduce the failure rate of components and improve the system's reliability. Therefore, the system's structure function with load-sharing applied functions at seven values of the state vector $\underline{x}$: (1,1,2), (1,2,1), (1,2,2), (2,1,1), (2,1,2), (2,2,1), and (2,2,2). The corresponding survival signature, $\Phi(l_1, l_2, l_3)$ for the system with load-sharing and without load-sharing applied, are given in Table 2, for all $l_1, l_2, l_3 \in \{0, 1, 2\}$.

Let the CDFs of the failure times of the components X_2, X_4, and X_{15} be

$F_1(t)$, $F_2(t)$ and $F_3(t)$, respectively. $R_k(t) = 1 - F_k(t)$ is the reliability function of components k at time t being $k = 1, 2, 3$. Then, the survival function for the system failure time T_s is

$$\begin{aligned} R_{sys}^{LS}(t) =& P(T_s > t) = \sum_{l_1=0}^{2} \sum_{l_2=0}^{2} \sum_{l_3=0}^{2} [\Phi(l_1, l_2, l_3) \\ & \cdot \prod_{k=1}^{3} \left(\binom{m_k}{l_k} [R_k(t)]^{l_k} [1 - R_k(t)]^{m_k - l_k} \right) \Bigg] \end{aligned} \tag{26}$$

In Equation (26), for the state vector $\underline{x}$ that $l_k = 2$, the term $\binom{m_k}{l_k}[R_k(t)]^{l_k}[1 - R_k(t)]^{m_k - l_k}$ will be replaced by the equation of load-sharing $R_k^{LS}(t)$. For different components of type $k \in \{1, 2, 3\}$, the reliability of the component of type k considering load-sharing is given as follows:

$$\begin{aligned} R_k^{LS}(t) =& e^{-(\tilde{\lambda}_k \cdot t)^{\tilde{\gamma}_k}} e^{-(\lambda_k \cdot t)^{\gamma_k}} + \tilde{\gamma}_k \cdot (\tilde{\lambda}_k)^{\tilde{\gamma}_k} \\ & \cdot \int_0^t u^{\tilde{\gamma}_k - 1} e^{-\left(\left[\lambda_k' (t-u) \right]^{\gamma_k'} + (\tilde{\lambda}_k u)^{\tilde{\gamma}_k} \right)} du + \gamma_k \cdot (\lambda_k)^{\gamma_k} \\ & \cdot \int_0^t u^{\gamma_k - 1} e^{-\left(\left[\tilde{\lambda}_k' (t-u) \right]^{\tilde{\gamma}_k'} + (\lambda_k u)^{\gamma_k} \right)} du \end{aligned} \tag{27}$$

where $\tilde{\lambda}_k$, $\tilde{\gamma}_k$ are scale and shape parameters of components taking sharing loads, λ_k, γ_k are scale and shape parameters of components taking full loads, $\tilde{\lambda}_k \leq \lambda_k$, $\tilde{\gamma}_k \leq \gamma_k$.

6. Results and discussions

The fuzzy failure rates of the basic events are obtained from the maintenance record provided by CSIC (Chongqing) Haizhuang Windpower Equipment Co., Ltd. The rotor diameter, the tower height, and the rated power are $111m$, $100m$ and 2.0 megawatt (MW), respectively. Due to the variable operating conditions and the uncertain failure rates, the failure rate of each component is represented by the triangular fuzzy number. The Markov chain is used to depict the fuzzy state of the hydraulic system. The basic events are represented by $X_i (i = 1, 2, \cdots, 19)$, and its corresponding fuzzy failure rate is $\tilde{p}_i (i = 2, 3, \cdots, 19)$ shown in Table 3.

Table 3: Failure rates represented by triangular fuzzy number of basic events

Basic events	Fuzzy failure rate $\tilde{p}_i(\times 10^{-6}/h)$	Basic events	Fuzzy failure rate $\tilde{p}_i(\times 10^{-6}/h)$
X_2	[1.6143, 3.2286]	X_{10}	[4.8921, 6.5234]
X_3	[4.8450, 6.5550]	X_{11}	[4.8450, 6.5550]
X_4	[1.6143, 4.6123]	X_{14}	[4.8921, 6.5234]
X_5	[0.0082, 0.0283]	X_{15}	[4.8450, 6.5550]
X_6	[0.5294, 0.8404]	X_{16}	[4.8921, 6.5234]
X_7	[0.0733, 0.3833]	X_{17}	[0.4612, 2.9982]
X_8	[0.0153, 0.2153]	X_{18}	[0.9281, 1.3781]
X_9	[4.8921, 6.5234]	X_{19}	[0.0425, 0.0575]

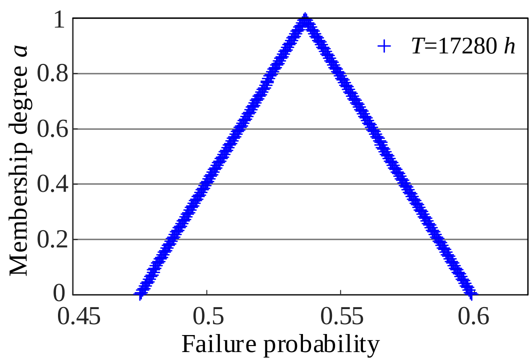

Figure 6: Membership of the fuzzy state $\tilde{f}_5(t)$

The fuzzy failure probability and the dynamic reliability of each state at different times can be calculated by solving equation (19). The FDFT theory is used to analyze the reliability of the WT hydraulic system.

Fig. 6 shows the membership function of the fuzzy failure probability of state S_5 at time t=117280 hours. The results of Fig. 6 show that the failure probability can gain the minimal value 0.4749 and the maximum value 0.5989 at cut level $\alpha = 0$, and gain the median value 0.5369 at cut level $\alpha = 1$ that is the most likely failure probability value of state S_5. Fig. 7 is the fuzzy reliability of the WT hydraulic system at the different α-cut level. The result of Fig. 7 shows that system reliability decreases with time. The system reliability gains the

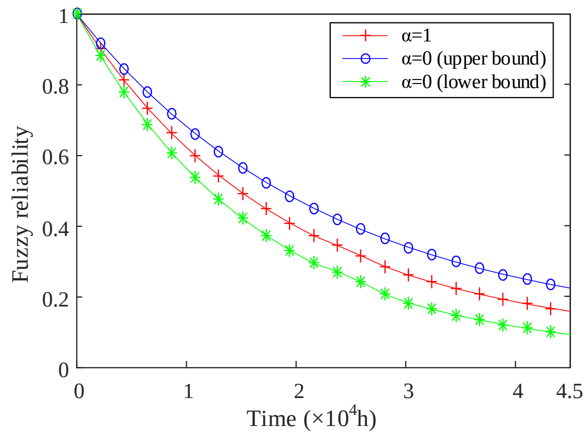

Figure 7: Fuzzy reliability of the hydraulic system at different membership degree

minimal value and maximum value at membership α=0. The reliability value at membership α=1 is the most likely reliability value at the corresponding time t and is always varying between the lower and upper bounds of the reliability at membership α=0. With the increase of the uncertainty of failure probability of basic events, the uncertainty of the reliability for the entire hydraulic system increases.

The load-sharing based reliability model using survival signature is explored in this article. The results of the reliability assessment using the proposed model are shown in Fig. 8. In this article, we also compare the results with that of the traditional methodologies [34]. The results of Fig. 8 show that the load-sharing with survival signature model can obtain the largest reliability value of the four reliability models, and the reliability values of the Markov-chain model and DFT model are second and third. However, the series-parallel model narrowly gets the smallest value, which is commonly used in reality. In wind turbines, many redundancy designs are adopted to improve the reliability of the weakest components and assemblies so that the system reliability can be maintained at a safe level. The components in the load-sharing system of wind turbines, whose failure rates are dependent, can share the total workload. However, these redundancy systems are often seen as parallel systems, in which

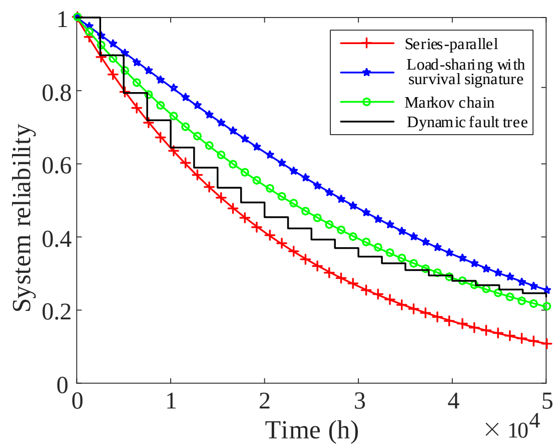

Figure 8: Reliability of the hydraulic system

components are independent and can not share the load. Therefore, treating the redundancy systems as parallel systems may bring a significant error to the reliability assessment of the system.

As can be seen from Fig. 8, the system reliability using series-parallel model would be clearly underestimated, which means designers have to allocate more reliability and resources to these components than they should get. The proposed load-sharing reliability model using survival signature can contribute to a more realistic assessment of the system reliability. The findings are in accordance with the reality that some components are allocated much higher reliability than normal, which leads to the prohibitive cost of WTs.

To identify the importance of each component, the reliability importance analysis is conducted. The reliability and reliability importance of the hydraulic system can be calculated using equation (6) and (7). Fig. 9 is the reliability importance of the redundant components of the hydraulic system. The solid line, the dotted line and the dashed line of Fig. 9 represent the reliability importance of the redundant components X_2, X_4, and X_{15}, respectively. The results of the reliability and reliability importance analysis suggest that components X_{15} are more important than X_2 and X_4, which means that the designers should pay attention to X_{15} and allocate more reliability and resources to X_2 and X_4.

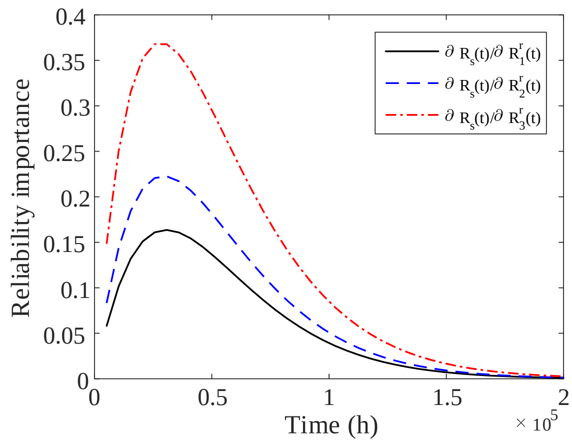

Figure 9: Reliability importance of the redundancy allocation

The reliability importance considers the probability that a component is critical for the system. However, reliability importance analysis can not explore the effects of probabilistic characteristics of components on their ranking [35]. Reliability sensitivity analysis has the complementary role of ordering by importance measures in determining the ranking. In this paper, the reliability sensitivity analysis using survival signature is also conducted using equation (9), the results of which are shown in Fig. 10. The reliability sensitivity of the hydraulic system with respect to the scale parameters of components X_4 and X_{15} is positive, which means that the reliability of the hydraulic system is quite sensitive to the uncertainties of the scale parameters of redundant components X_4 and X_{15}. The reliability sensitivity of the hydraulic system is not sensitive to the uncertainty of the scale parameter of component X_2 that has the highest reliability importance. Moreover, the reliability sensitivity with respect to the scale parameter of X_4 is larger than that of X_{15} ($\partial R_s(t)/\partial\lambda_2^r > \partial R_s(t)/\partial\lambda_3^r > \partial R_s(t)/\partial\lambda_1^r$). Therefore, compared with components X_2 and X_{15}, the uncertainty of the scale parameter of components X_4 has greater effects on the reliability of the hydraulic system than that of others.

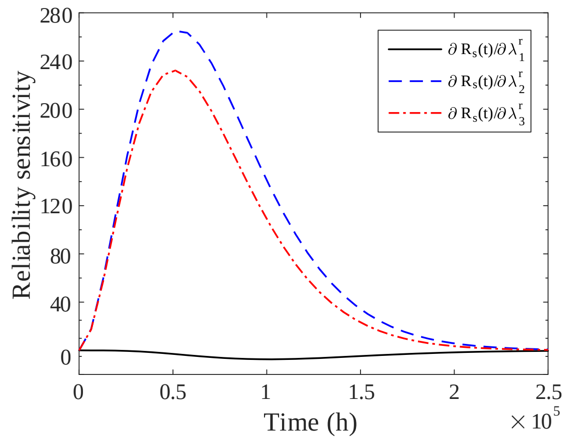

Figure 10: Reliability sensitivity with respect to scale parameters

7. Conclusion

The hydraulic system is used to reset the aerodynamic brakes of the wind turbine, which is quite important to the reliability and safety of the wind turbine. In engineering practice, the designers adopt many redundancy designs in the hydraulic system to improve the system reliability. In this paper, we conduct the reliability-redundancy allocation of the hydraulic system considering the constraints of cost and space. The number of redundant components of the hydraulic pump, one-way valve, and overflow valve is 2, 2 and 2. We propose the load-sharing based reliability model using survival signature to assess the reliability of the hydraulic system.

To verify the proposed model, we also explore the fuzzy dynamic fault tree model and Markov chain model of the hydraulic system. The dynamic fault tree model of the hydraulic system with dynamic failure characteristics and uncertain data is transformed into the fuzzy Markov chain model. The dynamic reliability of the hydraulic system is calculated using the fuzzy theory. The results of Fig. 7 show that the uncertainties of the failure probabilities of basic events may increase the uncertainty of the system reliability.

The results of different reliability models are compared in Fig. 8. We find that the system reliability would be clearly underestimated using series-parallel model. The proposed load-sharing reliability model using survival signature can contribute to a more realistic assessment of the reliability of the hydraulic system. Following this, the reliability importance and the reliability sensitivity of redundant components of the hydraulic system are explored in this paper as well. We quantitatively measure the reliability importance and the reliability sensitivity of redundant components and find that the one-way valve (X_4) and the overflow valve (X_{15}) are critical components that should be allocated more reliability and resources than others. The results show that the proposed method is a promising approach to reliability analysis of the complex system.

Author contribution statement

Dr. Yao Li (Writing & analysis - original draft). Prof. Frank Coolen (Analysis, review). Prof. Caichao Zhu (Writing, review). Dr. Jianjun Tan (Writing - Modifications).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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